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Experiments with Longitudinally Polarized Electrons in a Storage Ring Using a Siberian Snake

H. R. Poolman,[1,2] D. J. Boersma,[2] M. Harvey,[5] D. W. Higinbotham,[2,6] I. Passchier,[2] E. Six,[7] R. Alarcon,[7] P. W. van Amersfoort,[2] Th. S. Bauer,[3] H. Boer Rookhuizen,[2] J. F. J. van den Brand,[1] L. D. van Buuren,[1] H. J. Bulten,[1] R. Ent,[4,5] M. Ferro-Luzzi,[1,2] D. G. Geurts,[1] P. Heimberg,[1] C. W. de Jager,[4,6] P. Klimin,[8] I. Koop,[8] F. Kroes,[2] J. van der Laan,[2] G. Luijckx,[2] A. Lysenko,[8] B. Militsyn,[2] I. Nesterenko,[8] J. Noomen,[2] B. E. Norum,[6] M. J. J. van den Putte,[2] Yu. Shatunov,[8] J. J. M. Steijger,[2] D. Szczerba,[9] and H. de Vries[2]

[1]*Department of Physics and Astronomy, Vrije Universiteit, NL-1081 HV Amsterdam, The Netherlands*
[2]*NIKHEF, P.O. Box 41882, NL-1009 DB Amsterdam, The Netherlands*
[3]*Physics Department, Utrecht University, NL-3508 TA Utrecht, The Netherlands*
[4]*TJNAF, Newport News, Virginia 23606*
[5]*Department of Physics, Hampton University, Hampton, Virginia 23668*
[6]*Department of Physics, University of Virginia, Charlottesville, Virginia 22901*
[7]*Department of Physics, Arizona State University, Tempe, Arizona 85287*
[8]*Budker Institute for Nuclear Physics, Novosibirsk, 630090 Russian Federation*
[9]*Institut für Teilchenphysik, Eidgenossische Technische Hochschule, CH-8093 Zürich, Switzerland*

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We report on first measurements with polarized electrons stored in a medium-energy ring and with a polarized internal target. Polarized electrons were injected at 442 MeV (653 MeV), and a partial (full) Siberian snake was employed to preserve the polarization. Longitudinal polarization at the interaction point and polarization lifetime of the stored electrons were determined with laser backscattering. Spin observables were measured for electrodisintegration of polarized ^{3}He, with simultaneous detection of scattered electrons, protons, neutrons, deuterons, and ^{3}He nuclei, over a large phase space.

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In the scattering of leptons from hadronic targets, the leptonic part of the interaction is well understood, allowing one to focus on the strong-interaction vertex and the underlying structure and dynamics of the nucleus. The ultimate probe consists of spin-dependent scattering with polarized leptons and polarized targets [1], and the last decade has seen a large effort devoted to the realization of such experiments.

Most experiments used electrons beams impinging on external polarized targets to achieve adequate luminosity. In this way, data on, e.g., the neutron form factors and deep-inelastic structure functions have been obtained (see, e.g., [2–7]). Although typically lower in luminosity, spin-dependent electron scattering experiments from polarized gas targets internal to storage rings have the advantages: (i) they can be well matched with the use of large-acceptance detectors; (ii) rapid polarization reversal and flexible orientation of the nuclear target spin can be obtained, reducing systematical uncertainties; (iii) low-energy recoiling particles can escape the ultrathin targets and can be detected, allowing a complete reconstruction of the final state in the electrodisintegration of few-body systems. So far, electromagnetic spin-correlation observables from internal gas target experiments have been obtained only at DESY [7] in the deep-inelastic scattering regime. There the electron beam energy is high enough that transverse polarization builds up through the Sokolov-Ternov effect [8].

For a study of nuclear structure and dynamics in both the quasifree scattering and Δ-resonance region, electron beams with energies up to 1 GeV are optimal: one may achieve resolutions in energy and momentum sufficient to distinguish various nuclear states and details in the wave functions; one can keep the momentum transfer small to optimize the sensitivity to long-distance nucleon and nuclear physics effects, while detection of heavily ionizing recoiling nuclear particles yields increased sensitivity to coherent effects in the nuclear dynamics. However, for such low electron beam energies the self-polarizing time is too long to take advantage of, and one has to inject polarized electrons and rely on Siberian-snake techniques. An experiment with the VEPP-2M collider at BINP, Novosibirsk [9], demonstrated that with such a solenoid (i.e., snake) the polarization of a 440 MeV positron beam can be maintained while crossing an integer resonance. A series of measurements has been carried out with proton beams at the Indiana University Cooler Ring [10] and the Brookhaven Alternating Gradient Synchrotron [11]. However, problems from quantum fluctuations by synchrotron radiation, which depolarize electron beams, are absent in experiments with proton beams.

Here, we report on first measurements utilizing all aspects of spin-dependent scattering in a medium-energy storage ring with longitudinally polarized electrons incident on a polarized internal gas target. The experiment was performed at the Amsterdam Pulse Stretcher (AmPS) ring [12] at NIKHEF. When electrons are injected into AmPS with their polarization axis oriented in the ring plane, their spins will precess around the vertical fields provided by the dipole magnets in the ring. Because the electron helicity is conserved in the extreme relativistic limit, electron scattering experiments require electrons with longitudinal polarization [1]. Asymmetries measured with transverse electron beam polarization are suppressed by the Lorentz factor $\gamma = E_e/m_e c^2$, where E_e is the beam energy, m_e is the electron mass, and c is the speed of light. In AmPS, longitudinal polarization at the target position can be achieved when polarized electrons are injected at a specific in-plane spin angle and when the spin tune, which is the number of spin precessions (relative to its momentum) during one electron revolution, is equal to an integer. The spin tune is proportional to E_e, as $\nu_S = \frac{g_e-2}{2}\gamma$, where g_e is the magnetic g factor of the electron. The first "magic" energy, where $\nu_S = 1$, is encountered for $E_e = 440.65$ MeV. However, the electron energy is never exactly equal to a magic energy, and the spin precession caused by the small offset from the magic value will quickly dilute the longitudinal orientation of the spins. Also, imperfections in the horizontal field distribution of the storage ring can interact coherently with the spins of the electrons and cause rapid beam depolarization. But already a partial snake [11] produces the required closed spin orbit, thus providing stable operation near such so-called imperfection resonances in an electron storage ring, while a full snake should allow operation at any energy.

Figure 1 shows an overview of AmPS, with the main components relevant for the present discussion, such as the polarized electron source, snake, laser backscattering polarimeter, and polarized internal target.

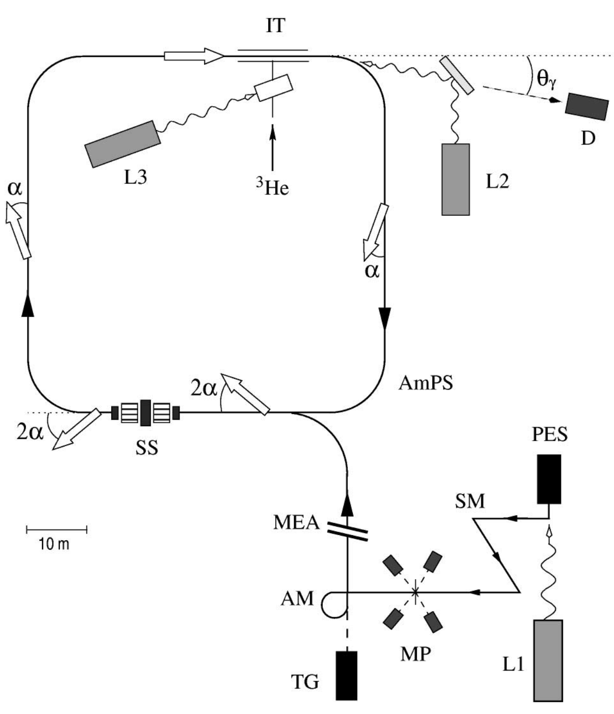

FIG. 1. Overview of the AmPS storage ring at NIKHEF showing the polarized electron source (PES), spin manipulator (SM), Mott polarimeter (MP), thermionic gun (TG), alpha magnet (AM), linear accelerator (MEA), Siberian snake (SS), CBP photon detector (D), and internal target (IT). Lasers are indicated with L1, L2, and L3. The stable in-plane polarization direction for stored electrons with the full snake on is illustrated.

Spin polarized electrons were obtained by means of photoemission from a semiconductor crystal which was prepared to a negative electron affinity surface state with cesium and oxygen. The crystal was illuminated with a 7 mm diameter circularly polarized light beam from a tunable (700–900 nm) flashlamp pumped Ti-sapphire laser. The polarization direction of the injected electrons can be rotated over arbitrary angles with a Z-shaped spin manipulator [13]. The polarization of the injected electrons was determined by Mott scattering at 100 keV from a 100 nm thick gold foil.

The snake is located in the straight section immediately after the injection kicker, on the side of the storage ring opposite to the internal target facility. It consists of two superconducting solenoids and five quadrupole magnets and is capable of providing a field integral of up to 10.5 T m. The spin rotation in the snake for ultrarelativistic electrons is given by $\phi = \frac{g_e e c}{2E_e}\int \mathbf{B}\cdot d\mathbf{l}$, with e the elementary charge. For a full snake, one has $\phi = \pi$, whereas the effective snake strength of a partial snake is given by $s = \phi/\pi$. For the present experiment, snake settings were selected with $s = 1$ and $s = 0.107$. Typically, several beam bunches (of 2 mA each) were stacked in the ring, yielding stored currents up to 150(30) mA with a full(partial) snake. A lifetime of about 20(3) min without(with) polarized gas in the internal target was obtained.

A Compton backscattering polarimeter (CBP) using an argon-ion laser system [14] measures the longitudinal polarization of the stored beam directly after the first 11.3° bending magnet located downstream of the internal target region. Although laser backscattering polarimeters have been operated successfully at SLAC [15], DESY [8], and CERN [16], no such measurements have been attempted below 1 GeV, where the small asymmetries and the significant background contributions from bremsstrahlung pose a challenge.

Figure 2 shows the longitudinal polarization as a function of the spin angles as measured with the CBP in the internal target region with a partial snake ($s = 0.107$) and a beam energy of 442 MeV. The spin manipulator was used to vary the spin angles, and the data demonstrate the expected spin rotation of the electron polarization. The results were obtained with a strained-layer InGaAsP crystal and the corresponding polarization determined with Mott scattering was $(69.8 \pm 1.3)\%$. It is observed that the maximum longitudinal polarization of the stored electrons at the internal target interaction point was $(61 \pm 4)\%$. We verified that the observed loss of electron polarization was independent on the amount of injected electron bunches, which allows one to increase the total current in the ring. Part of the loss is due to the polarization lifetime which renders an average polarization of the stored beam that is about 5% smaller than the injected beam polarization. The beam polarization was measured as a function of time over

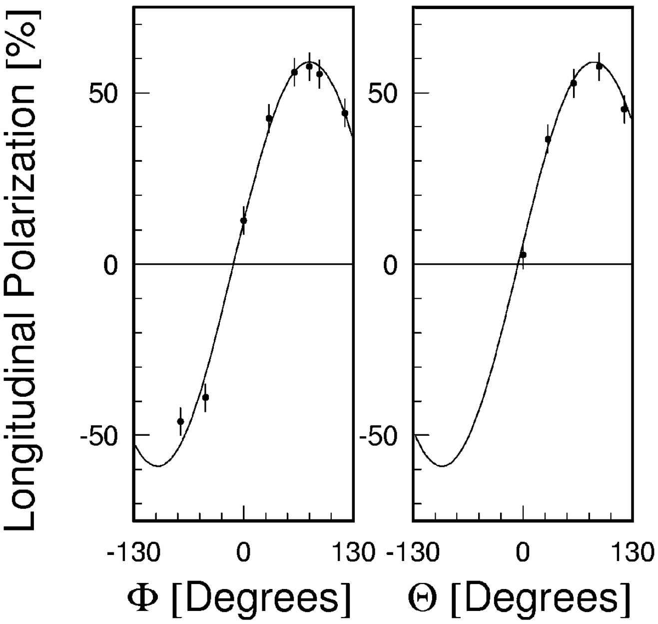

FIG. 2. Longitudinal polarization measured with the CBP versus spin angles set with the spin manipulator.

a period of about 300 s, i.e., the duration of a fill. The observed relaxation time $\tau = 4500^{+5600}_{-1600}$ s is in fair agreement with the predicted value $\tau_{\text{theory}} = 10\,707$ s [17]. The remainder of the polarization loss may be explained by dispersion effects in the various solenoidal magnetic elements in the linear accelerator. This is consistent with a measurement where $(42 \pm 3)\%$ polarized electrons from a GaAs crystal were injected with a longitudinal polarization direction into the linear accelerator in order to minimize such spin precession effects. These electrons were accelerated up to 653 MeV, an energy far away from the imperfection resonances at $\nu_S = 1, 2$. In this case, the longitudinal polarization determined with Compton scattering revealed no loss of polarization, apart from trivial spin-projection factors (i.e., the polarization direction was not longitudinal at the target position). These data constitute the first demonstration that polarized electrons can be injected and that their longitudinal polarization is preserved in an electron storage ring. Furthermore, we have shown that near the first magic energy the longitudinal polarization can be retained by operating a Siberian snake at about 10% of its nominal value.

A polarized ^{3}He internal target [18], based on the principle of metastability-exchange optical pumping [19], was used in the experiment. The polarized ^{3}He gas flowed from a glass pumping cell via a glass capillary into the internal target storage cell. An open-ended 400 mm long, 20 mm diameter cell was used in combination with a polarized electron beam of 442 MeV [20]. The storage cells were constructed of 50 μm thick ultrapure aluminum foils and cooled to 17 K to increase the target gas density, yielding a target thickness of $t = 7 \times 10^{14}$ atoms/cm^2. A target polarization of $P_T = (43 \pm 2)\%$ was achieved, limited by the influence of magnetic field gradients of the electron spectrometer magnet.

Scattered electrons were detected at angles $55° \leq \theta_e \leq 65°$ in the BigBite spectrometer, which consists of a 1 T dipole magnet, two sets of drift chambers, a scintillator, and an aerogel Čerenkov detector [21]. This spectrometer has a momentum resolution of 0.5%, a momentum acceptance of >50%, and a solid angle of 96 msr. Knocked-out protons and deuterons were measured in a range telescope [22] positioned at a central angle of 60°, and covering a solid angle of 180 msr. Protons in the range of 21–150 MeV and deuterons in the range of 23–200 MeV were detected with an energy resolution of about 3% (FWHM). Neutrons were measured by using a time-of-flight detector, consisting of eight telescopes arranged in two walls of 160×80 cm^2 front surface. Each telescope consists of three layers of scintillator, with a thickness of 3 mm, 10 mm, and 200 mm, respectively. Each scintillator had a double-sided readout by photomultiplier tubes (PMT). A neutron was selected as a coincidence between the two PMTs on the 200 mm thick bars and a (8–12)fold veto by all surrounding scintillators. Each wall covered approximately 200 msr and had a neutron detection efficiency of about 20%.

In addition, a silicon-strip detector was integrated in the target vacuum chamber at a distance of 20 cm from the storage cell, allowing detection of low-energy recoiling hadrons [23]. This detector provides a calibration of the product of beam and target polarization, by monitoring elastic scattering asymmetries [24]. Furthermore, data were collected on coherent, spin-dependent pion electroproduction by detecting the recoiling ^{3}He and tritons.

The main contribution ($\approx$90%) to the ^{3}He ground-state wave function is predicted to be a spatially symmetric S state, where the protons occupy a spin-singlet state [25]. In consequence, the spin correlation parameter A'_z, where the nuclear polarization is oriented along the momentum transfer, is expected to be small for the $^3\vec{\text{He}}(\vec{e}, e'p)$ reaction, whereas for the $^3\vec{\text{He}}(\vec{e}, e'n)$ reaction it is expected to be large. Table I shows the spin correlation parameter A'_z measured at a beam energy of 442 MeV and a central scattering angle of 60°, at an average momentum transfer of $Q^2 = 0.16\ (\text{GeV}/c)^2$ Because of limited statistics the quasifree scattering events within the acceptance of

TABLE I. Data and theoretical predictions [26] for the longitudinal spin correlation parameter A'_z for the reactions $^3\vec{\text{He}}(\vec{e}, e'p)$ and $^3\vec{\text{He}}(\vec{e}, e'n)$ at a beam energy of 442 MeV and at $Q^2 = 0.16(\text{GeV}/c)^2$. The calculations were performed for the central electron kinematics at a scattering angle of $\theta_e = 60°$.

A'_z	Theory FULL	Theory Plane wave impulse approximation	Data
$(\vec{e}, e'p)$	0.071	0.065	0.15 ± 0.11
$(\vec{e}, e'n)$	-0.55	-0.79	-0.56 ± 0.18

the detector setup were combined in the datum in Table I. The FULL result represents a 34-channel solution of the Faddeev equations for the three-body system using the Bonn-B potential. These calculations, performed by Golak *et al.* [26], include rescattering effects up to all orders. The calculations were restricted to the central electron kinematics of the experiment. A Monte Carlo technique was used to determine the phase space covered by the ejected hadrons. We find good agreement between data and calculational results.

In summary, we have performed first measurements using an injected and stored longitudinally polarized electron beam in a storage ring. The longitudinal polarization of the electron beam at 442 MeV was successfully preserved with a partial Siberian snake. In addition, first data were presented for the longitudinal spin correlation A_z' for the $^3\vec{\mathrm{He}}(\vec{e}, e'p)$ and the $^3\vec{\mathrm{He}}(\vec{e}, e'n)$ reactions. Although these data are still of limited statistical significance, they demonstrate that it is technically possible to perform spin-dependent electron scattering experiments in a medium-energy electron storage ring. A full exploration of polarization observables [27,28] will permit a detailed investigation of the relevant degrees of freedom in electrodisintegration of the few-body systems, the measurement of spin-dependent momentum distributions, and may address the isobar content of nuclear wave functions in pion electroproduction experiments.

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